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Title: New analogies between extreme QCD and cold atoms

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Web

title: "New analogies between extreme QCD and cold atoms"

abstract:
We discuss two new analogies between extreme QCD and cold atoms. One is the analogue of "hard probes" in cold atoms. The other is the analogue of "quark-hadron continuity" in cold atoms.

New analogies between xQCD and cold atoms

Yusuke Nishida (LANL)

Extreme QCD 2012

August 21-23 (2012)

LA-UR-12-?????

Plan of this talk

1. “Hard probes” in cold atoms

- Using energetic atoms to locally probe strongly-interacting atomic gases

- Y.N., Phys. Rev. A (2012) [arXiv:1110.5926]

2. “Quark-hadron continuity” in cold atoms

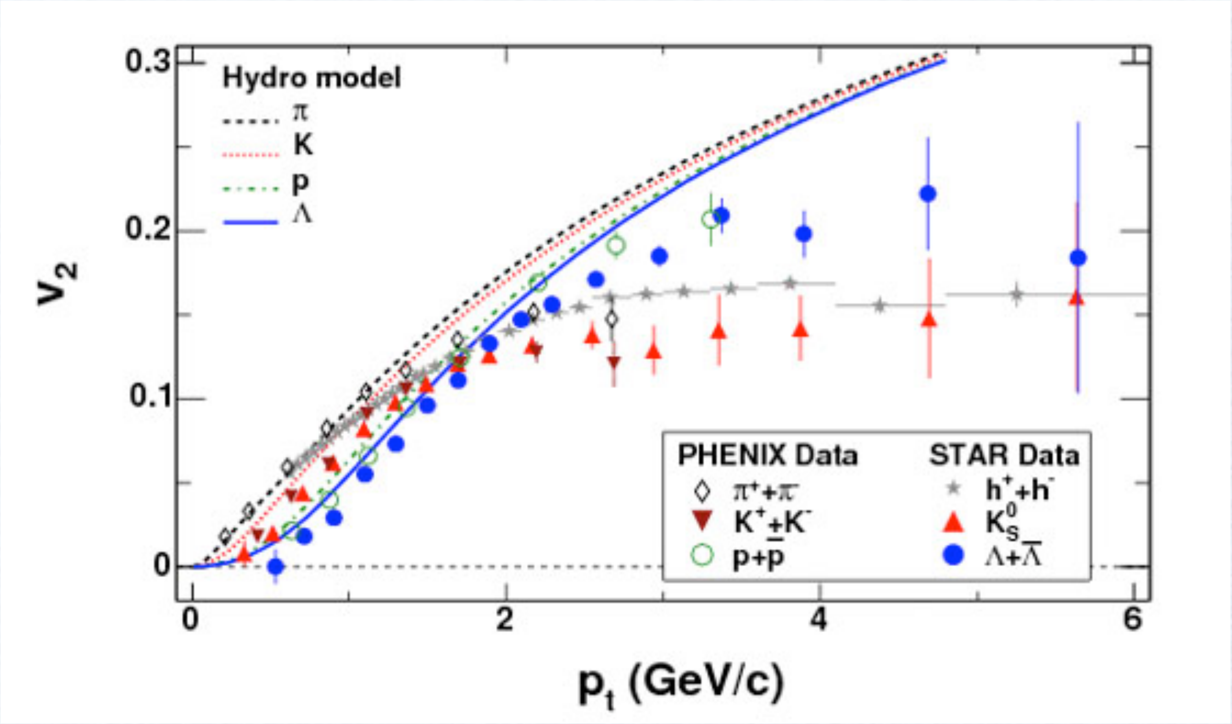
- Possible smooth connection between atoms and trimers in 3-component Fermi gases

- Y.N., arXiv:1207.6971

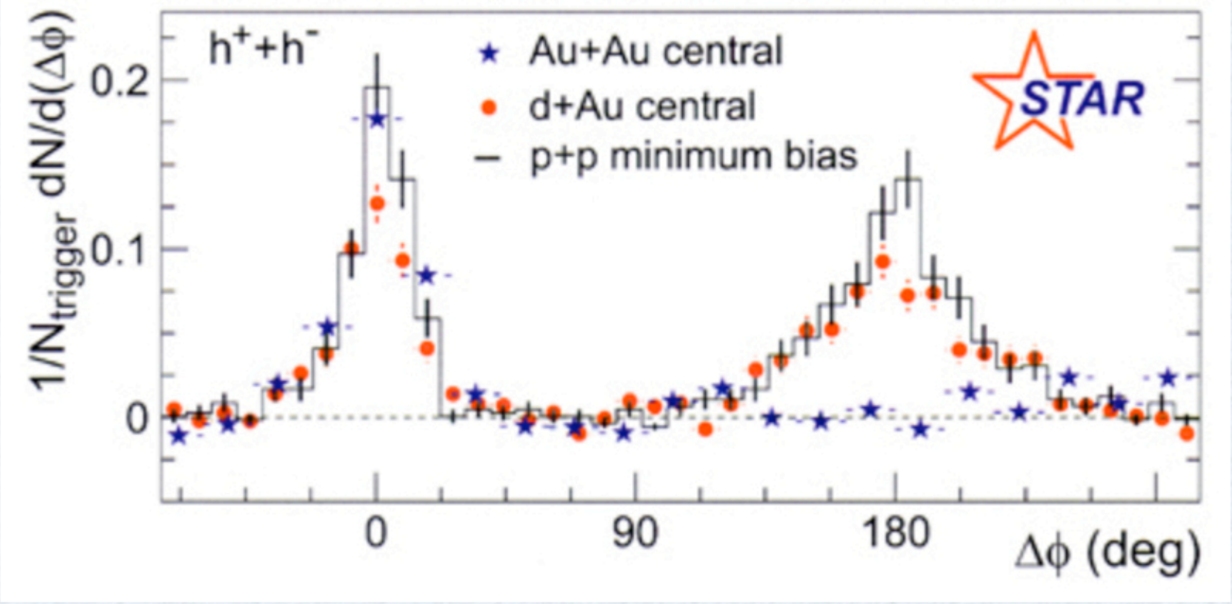
"Hard probes" in cold atoms

xQCD vs. cold atoms

- **Elliptic flow**



- **Jet quenching**

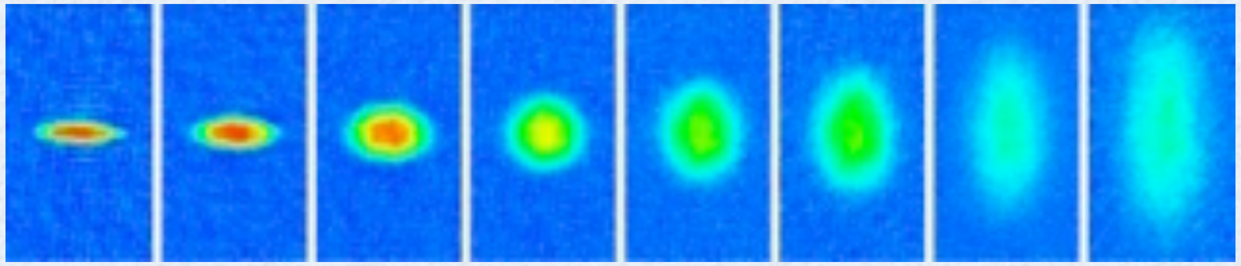


- **Small shear viscosity**

$$\frac{\eta}{s} \gtrsim \frac{1}{4\pi}$$

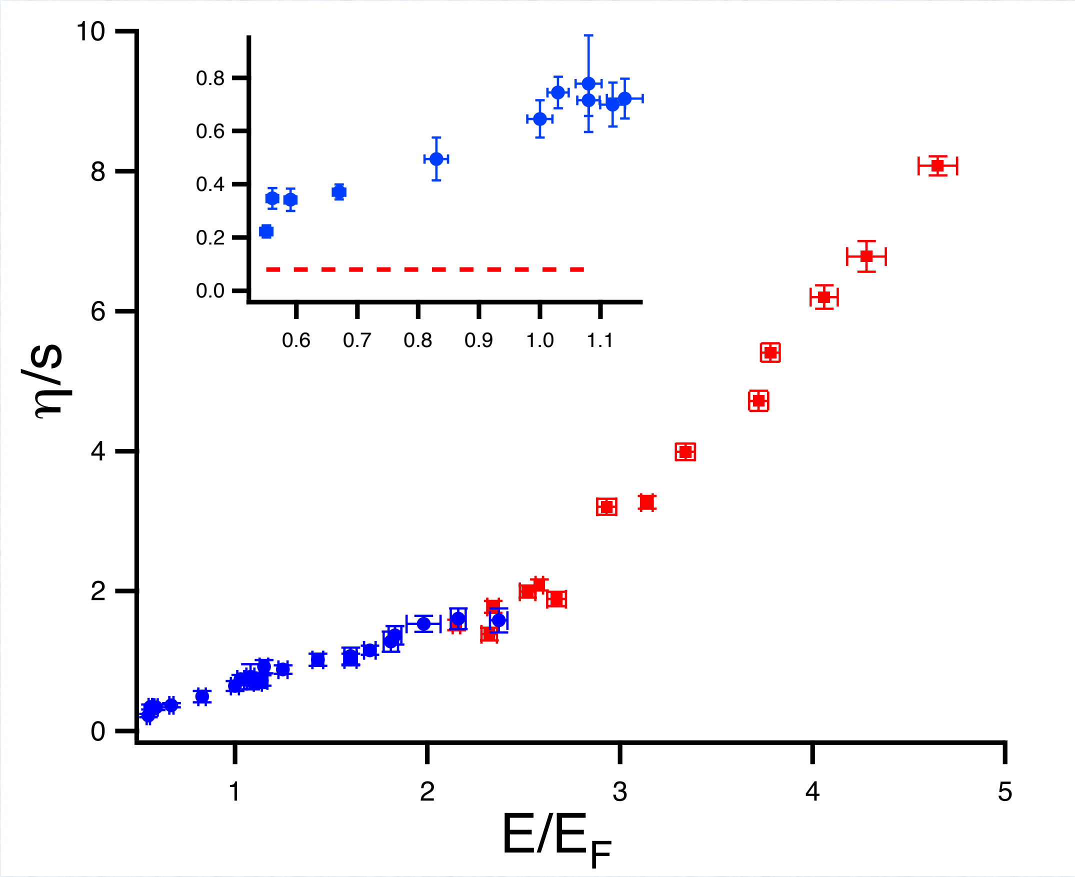
xQCD vs. cold atoms

- Elliptic flow



K. M. O'Hara et al., Science (2002)

- Small shear viscosity



C. Cao et al., Science (2011)

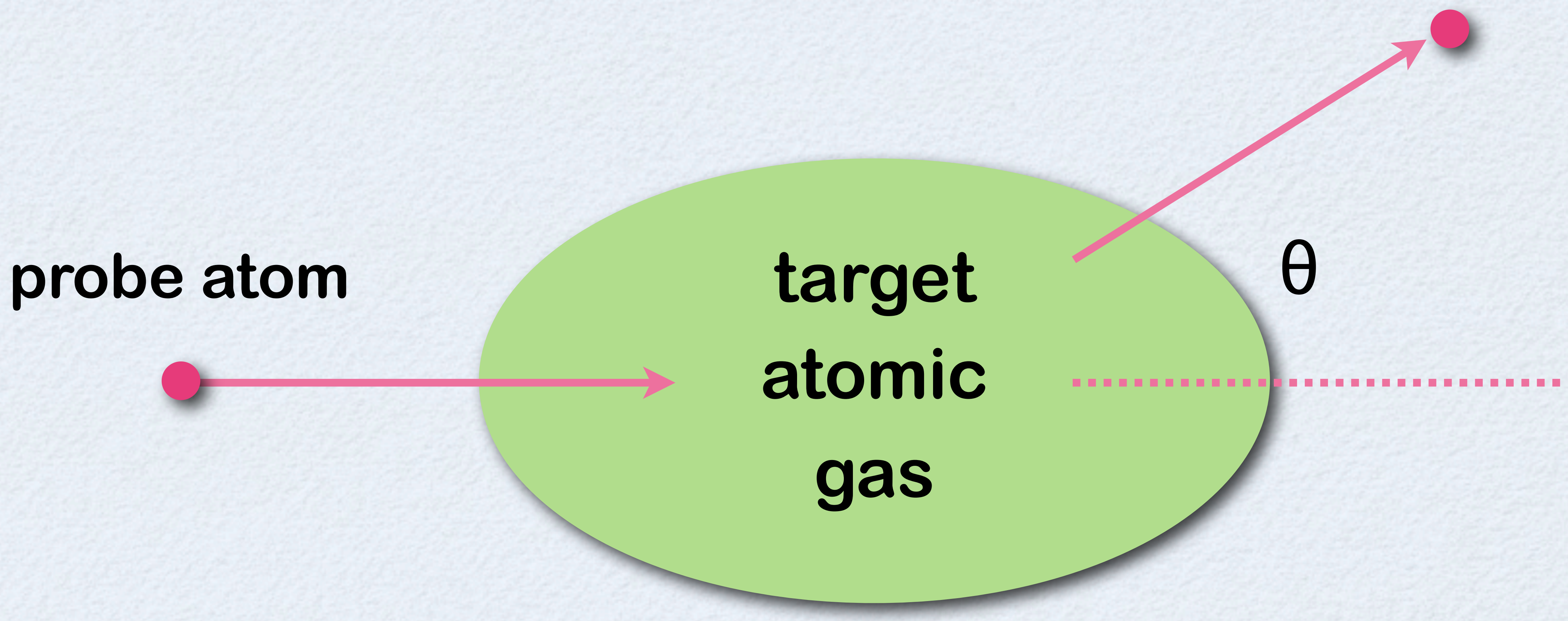
- Jet quenching

???

What is its analogue in cold atoms ?

Probe atomic gas with atoms

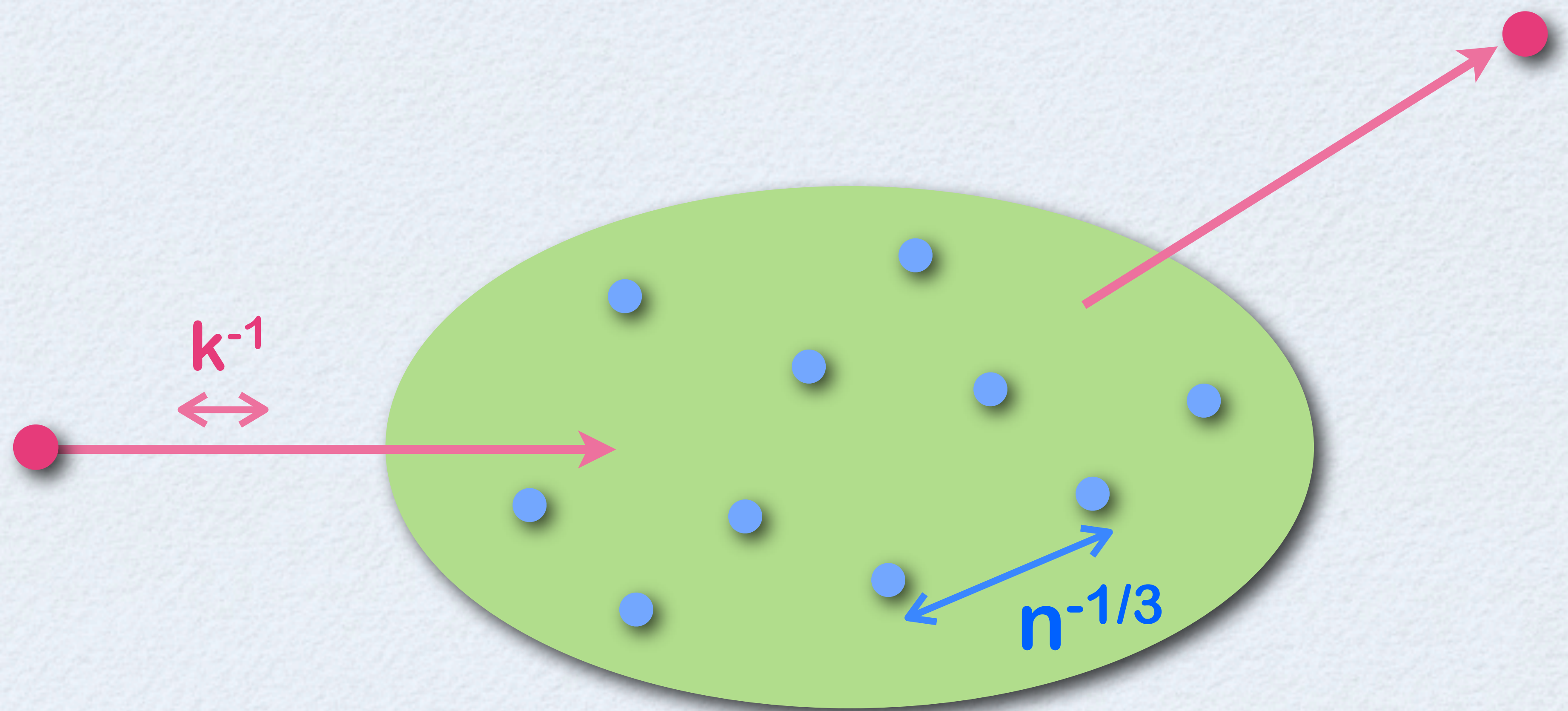
Shoot a probe atom into the target atomic gas
and measure its differential scattering rate



What can we learn from the scattering data
on the (strongly-interacting) target atomic gas ?

Probe atomic gas with atoms

Shoot a probe atom into the target atomic gas and measure its differential scattering rate

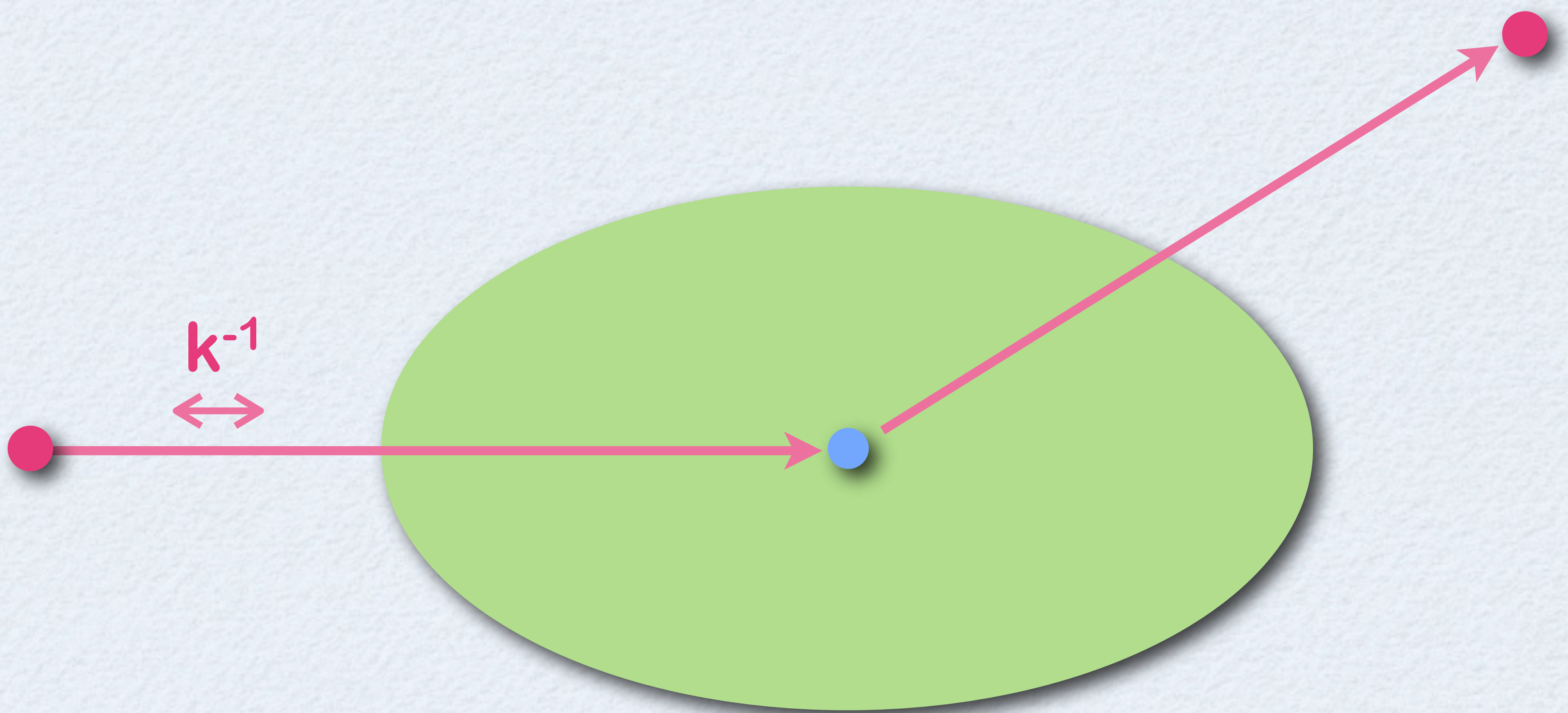


Large $k \gg n^{1/3}$ ⇒ Few-body scattering problems

$$\frac{d\Gamma(k)}{d\Omega} = \cdots$$

Leading contribution

Shoot a probe atom into the target atomic gas and measure its differential scattering rate

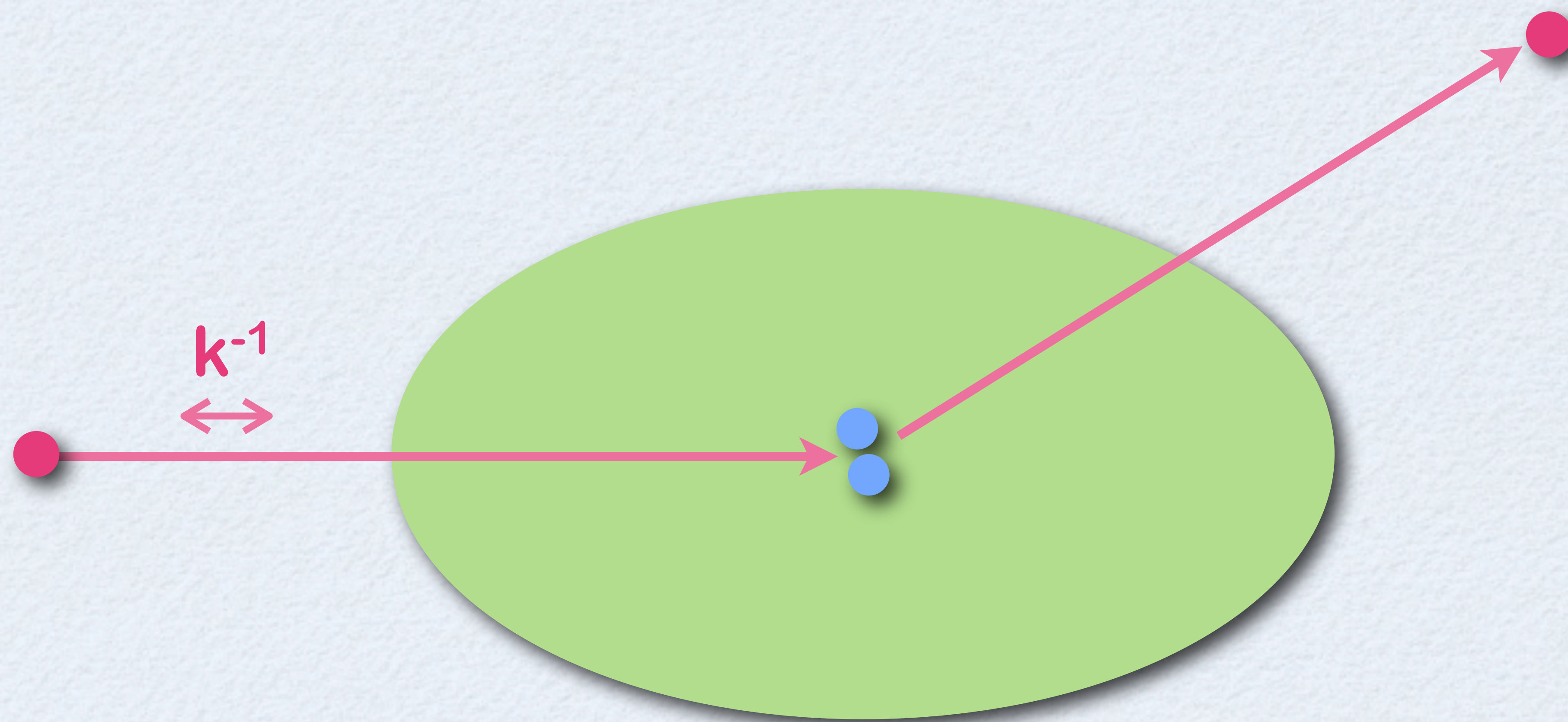


Large $k \gg n^{1/3}$ ⇒ Few-body scattering problems

$$\frac{d\Gamma(k)}{d\Omega} = f(\theta)\,\frac{n}{k} + \cdots$$

Sub-leading contribution

Shoot a probe atom into the target atomic gas and measure its differential scattering rate



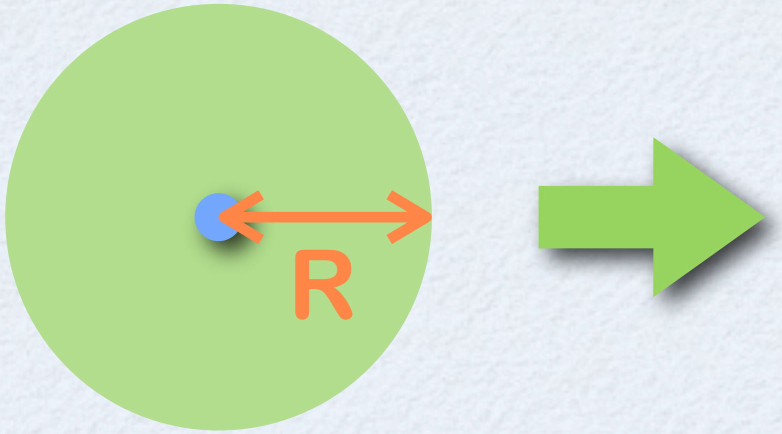
Large k ≫ $n^{1/3}$ ⇒ Few-body scattering problems

$$\frac{d\Gamma(k)}{d\Omega} = f(\theta)\,\frac{n}{k} + g(\theta)\,\frac{C}{k^2} + \cdots$$

What is “C” ?

Probability of finding 2 particles at small separation

- **noninteracting gas :** $\langle \hat{n}(r)\hat{n}(0)\rangle = n^2$
- **interacting gas :** $\langle \hat{n}(r)\hat{n}(0)\rangle \rightarrow \dfrac{C}{(4\pi|r|)^2}$



$$\int_{|r|<R} \langle \hat{n}(r)\hat{n}(0)\rangle \sim \begin{cases} n^2 R^3 \\ C\,R \end{cases}$$

Anomalously enhanced probability is quantified by the “contact density” C

Important characteristic of strongly-int atomic gases

S. Tan, Ann. Phys. (2009); E. Braaten & L. Platter PRL (2008)

Formulations à la OPE

- scattering rate : $\Gamma(k) = -2\,\mathrm{Im}\,\Sigma(k)$
- optical theorem : $\Gamma(k) = \int d\Omega\, \frac{d\Gamma(k)}{d\Omega}$

$$iG(k) = \int dx\, e^{ikx} \langle T\, \psi(x)\psi^\dagger(0)\rangle$$
$$= \sum_i A_i(k)\langle O_i\rangle$$

$$n = \langle \psi^\dagger \psi\rangle,\ \ C = \langle (\psi^\dagger\psi)^2\rangle,\ \ \ldots$$

Lowest few O_i are needed at large k

Systematic large-k expansion !

Differential scattering rate

Many-body physics

$$\frac{d\Gamma(k)}{d\Omega} = f(\theta)\,\frac{n}{k} + g(\theta)\,\frac{C}{k^2} + \cdots$$

Few-body physics

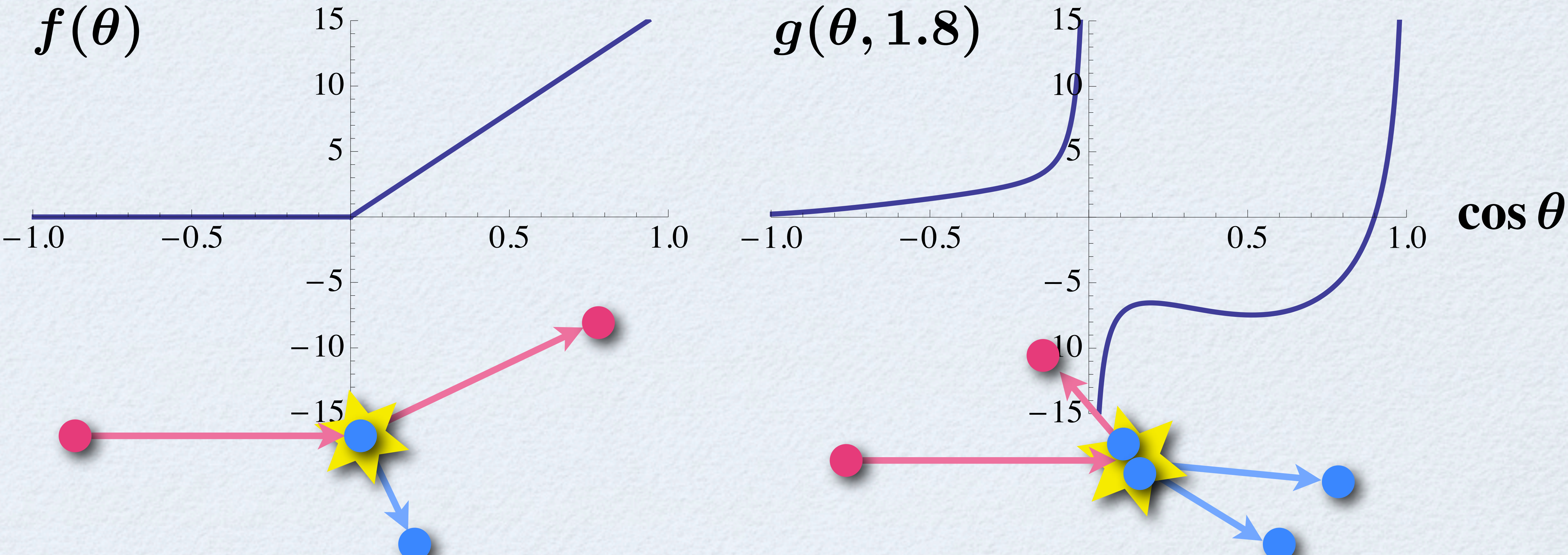
Few-body physics plays an important role to probe many-body physics !

Differential scattering rate

$$\frac{d\Gamma(k)}{d\Omega} = f(\theta)\,\frac{n}{k} + g(\theta, k/\kappa_*)\,\frac{C}{k^2} + \cdots$$

For zero-range interactions

Efimov effect



forward scattering (θ<90°) only

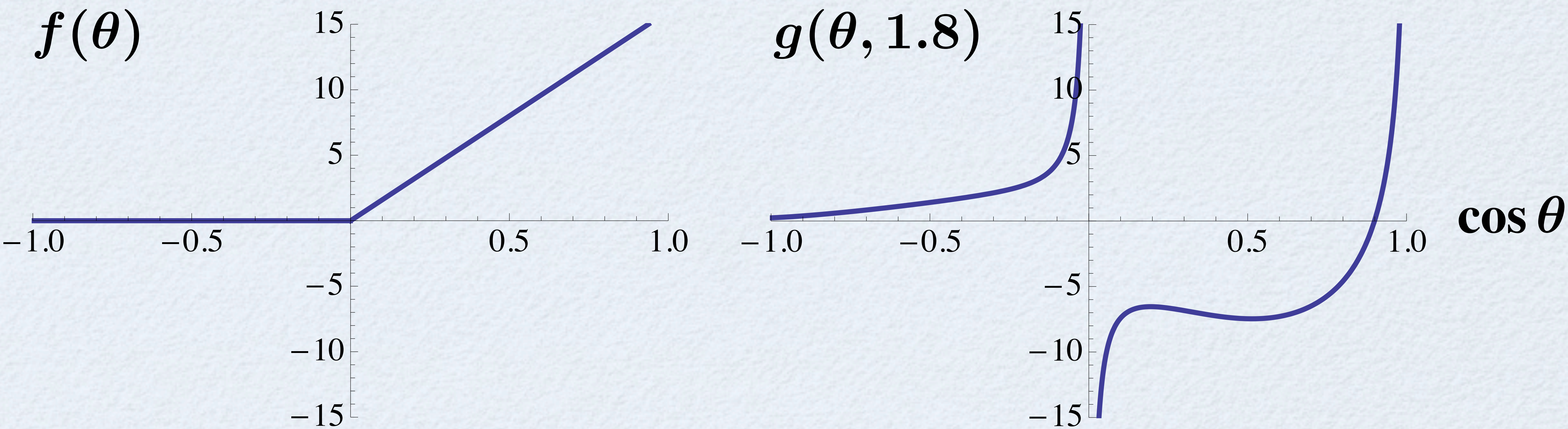
backward scattering (θ>90°) possible

Differential scattering rate

$$\frac{d\Gamma(k)}{d\Omega} = f(\theta)\,\frac{n}{k} + g(\theta, k/\kappa_*)\,\frac{C}{k^2} + \cdots$$

For zero-range interactions

Efimov effect

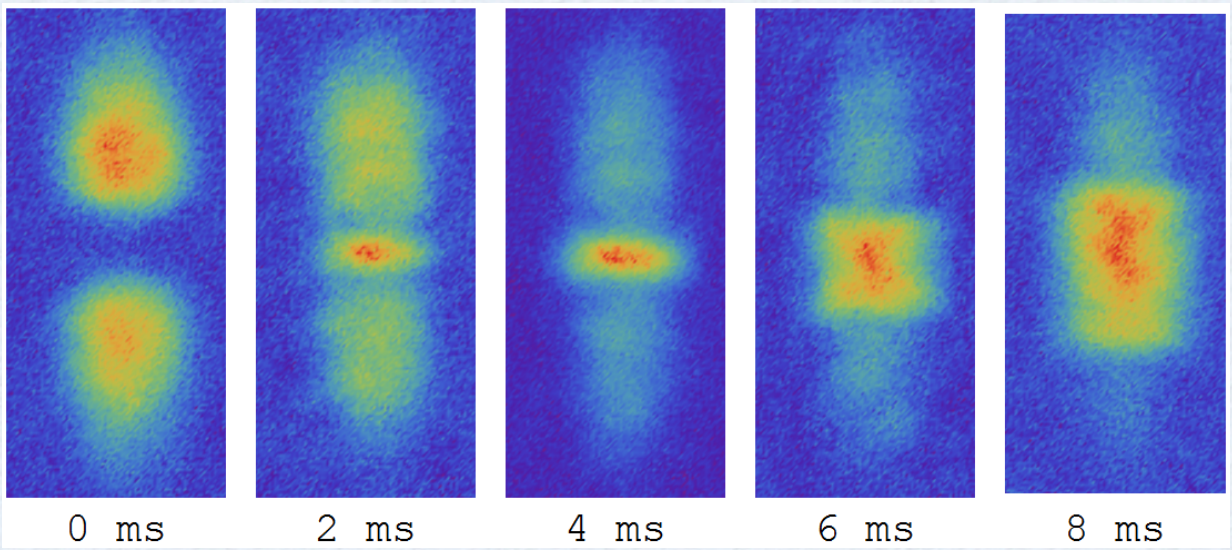


Backward scattering rate measures contact density

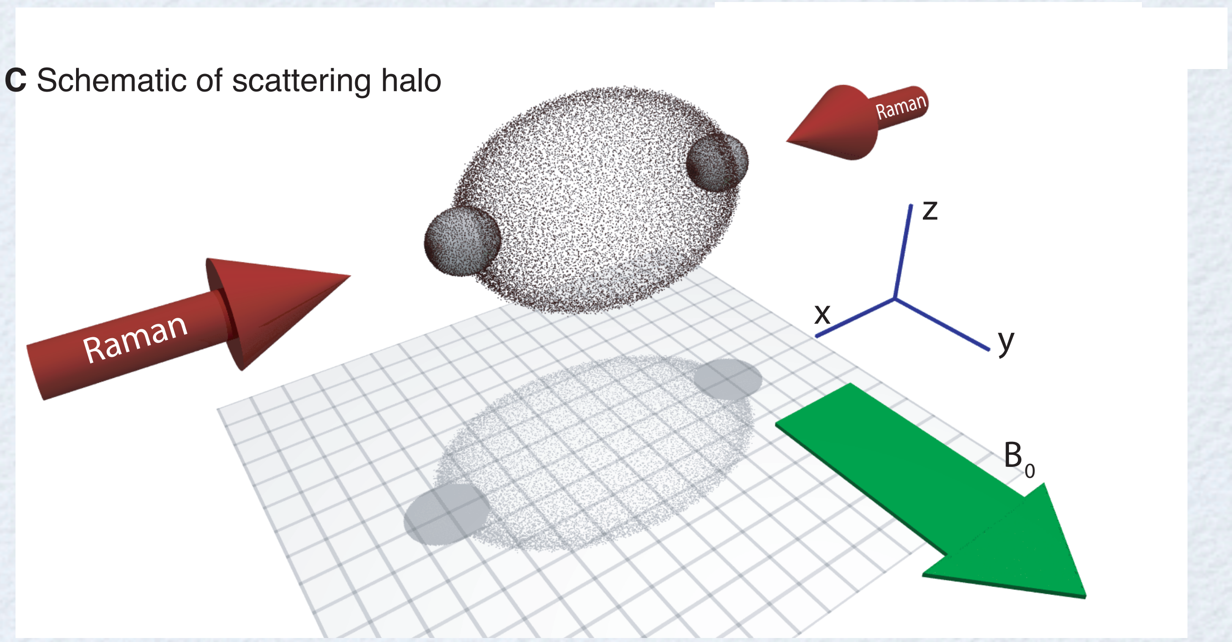
New local probe of strongly-int atomic gases

Ultracold atom “colliders”

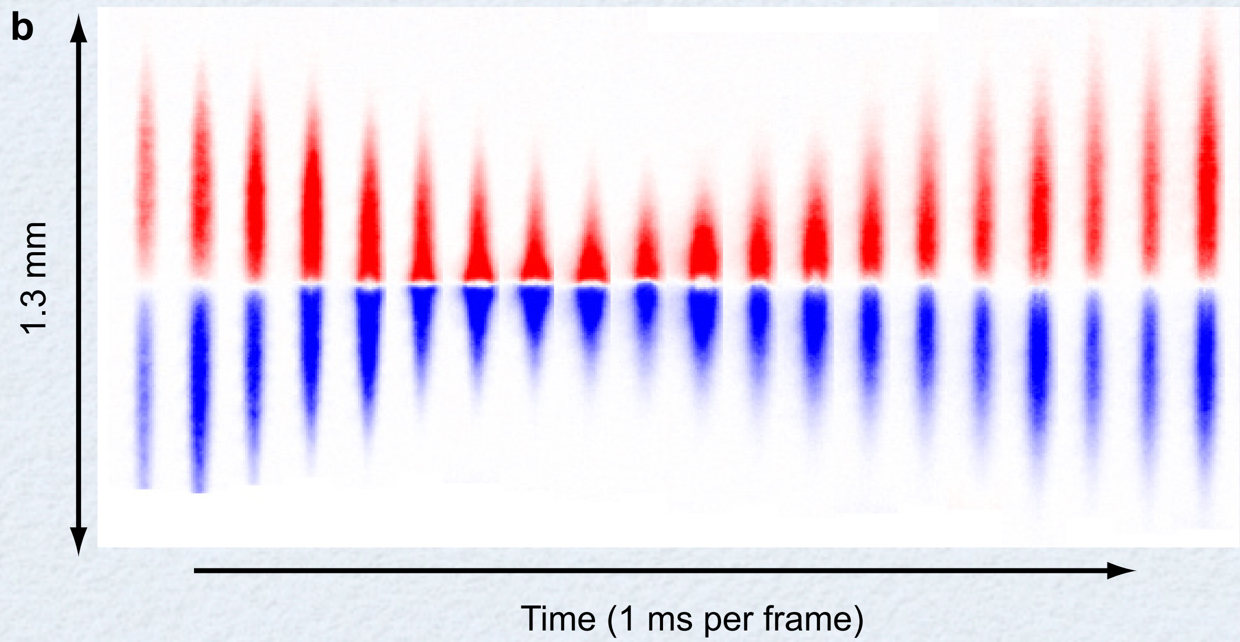
Duke (2011)



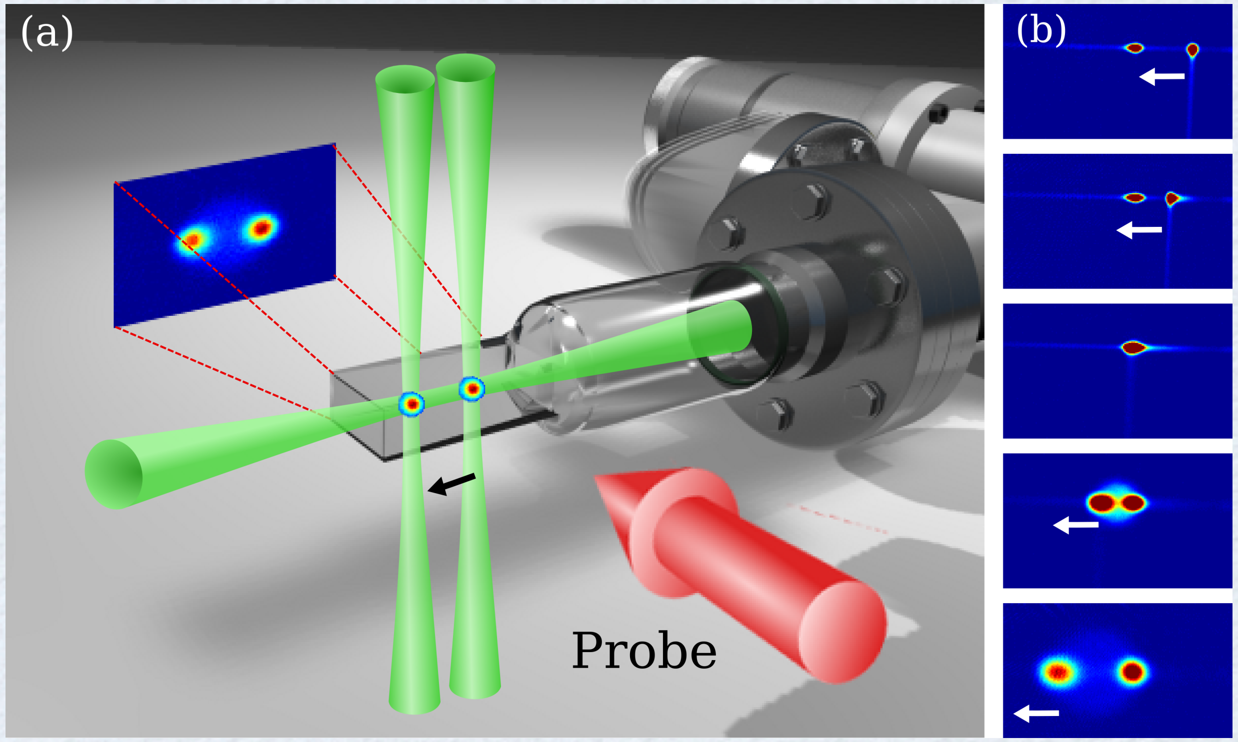
NIST (2012)



MIT (2011)

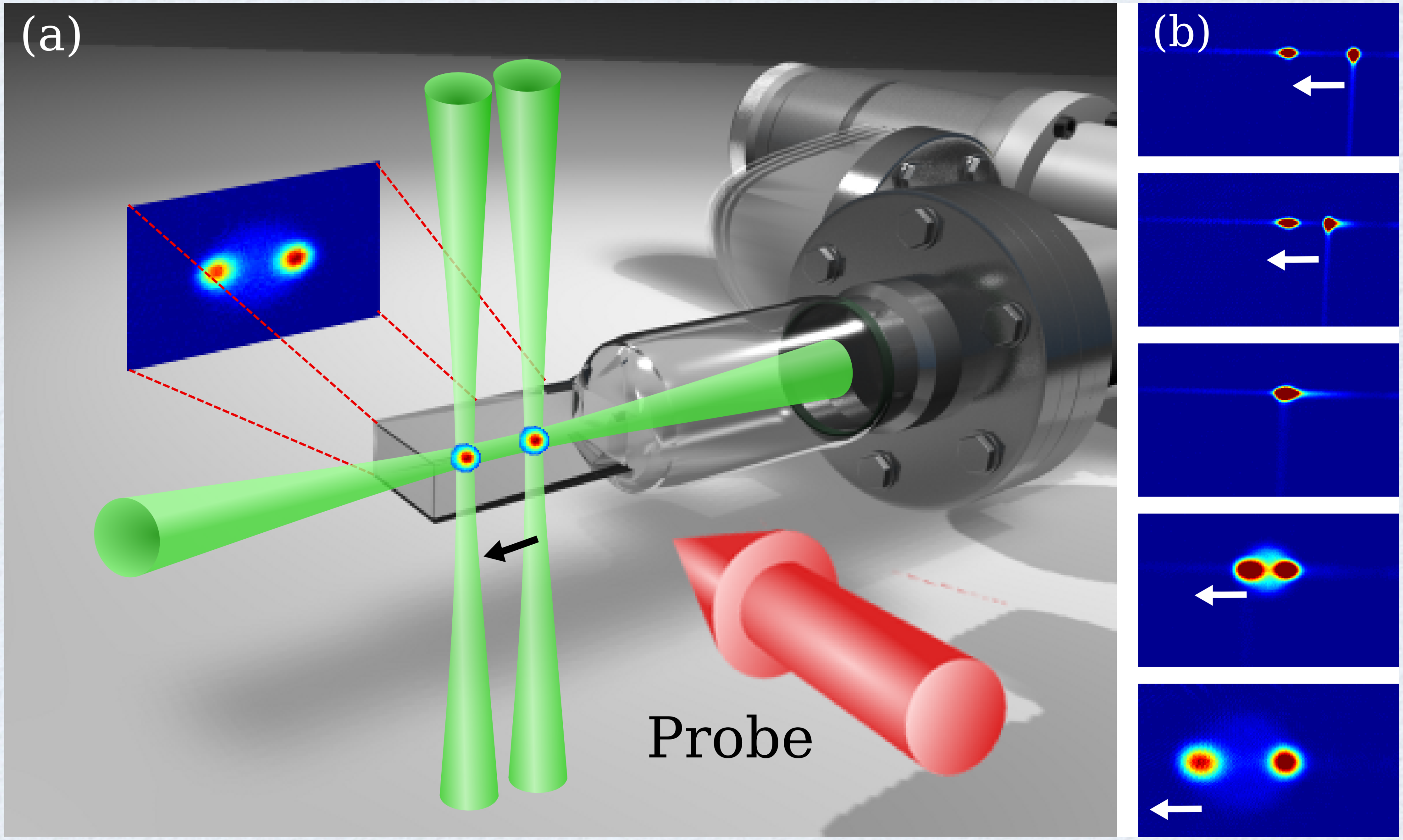


Otago (2012)



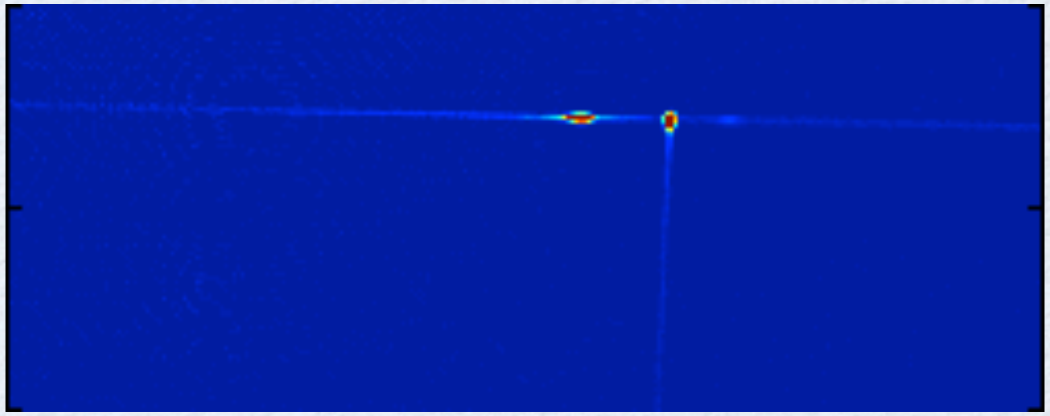
Ultracold atom "colliders"

"A laser based accelerator for ultracold atoms"



University of Otago (New Zeeland)

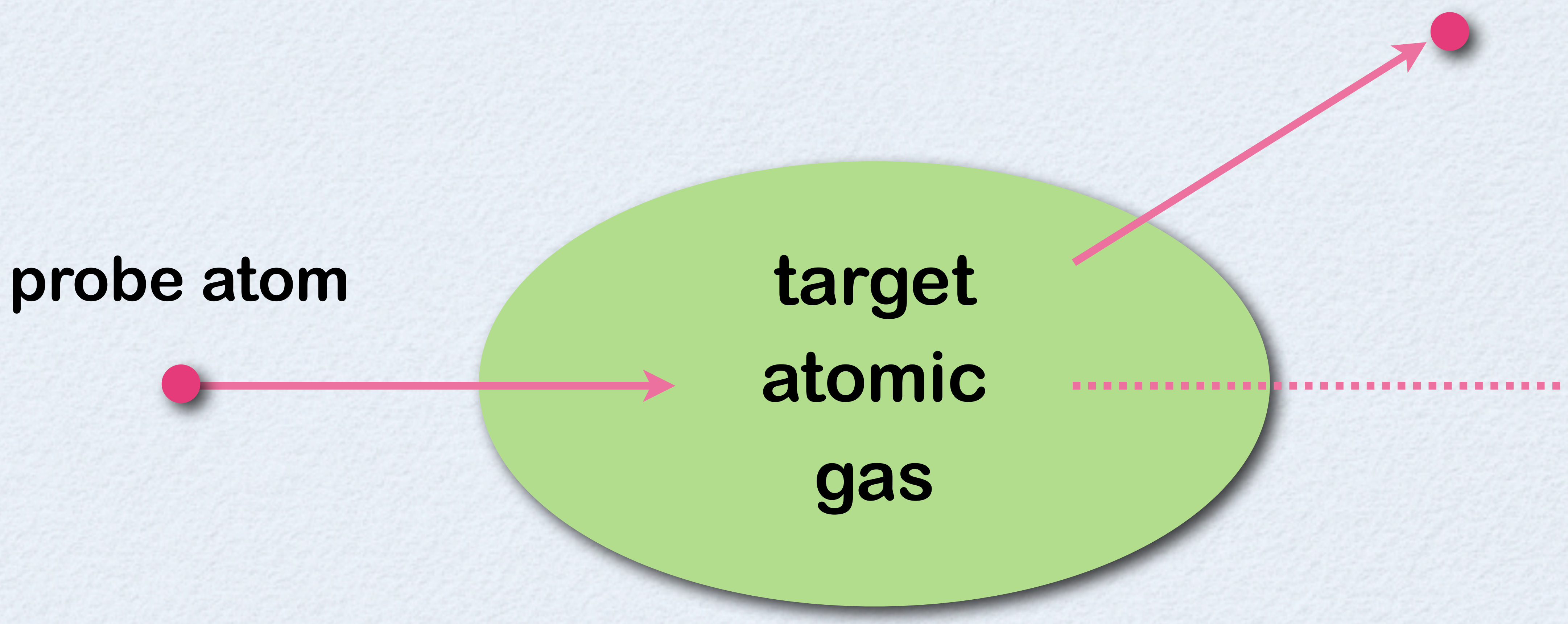
Optics Letters (2012)



Short summary 1

- Energetic atoms ⇒ New tool to locally probe strongly-interacting atomic gases
- Systematic large-k expansions are possible

  ✓ backward scattering ⇒ contact density

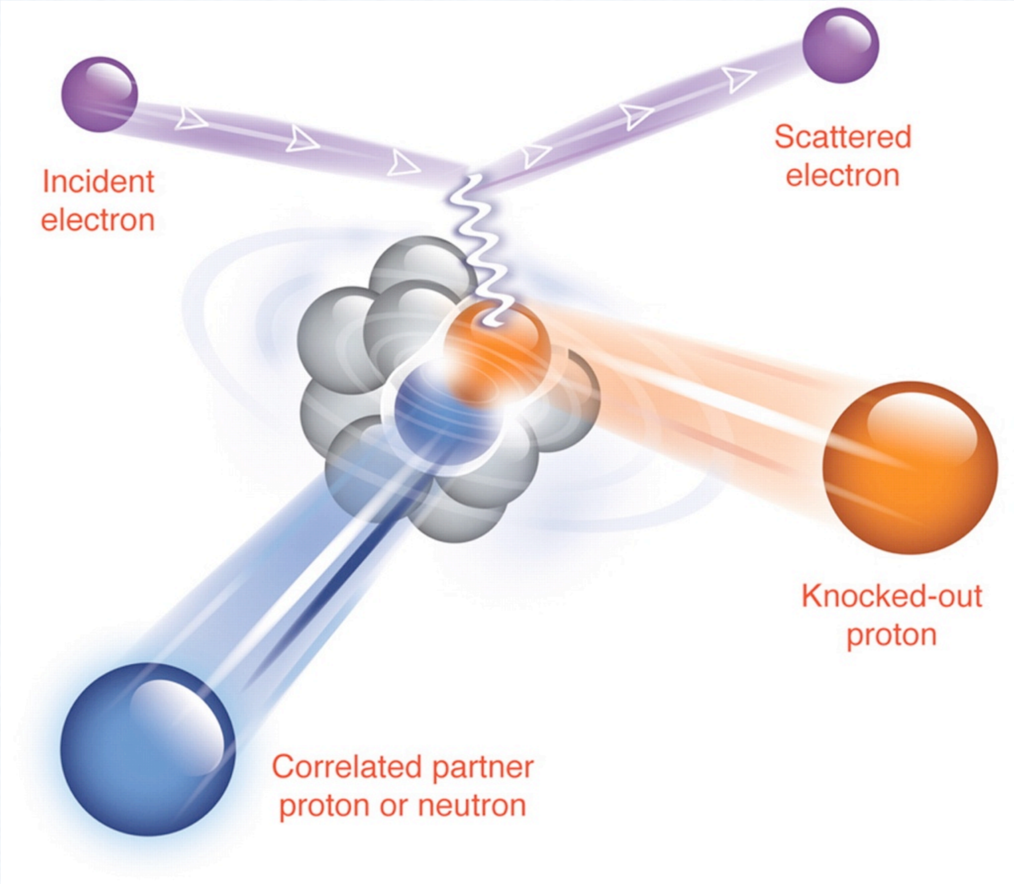


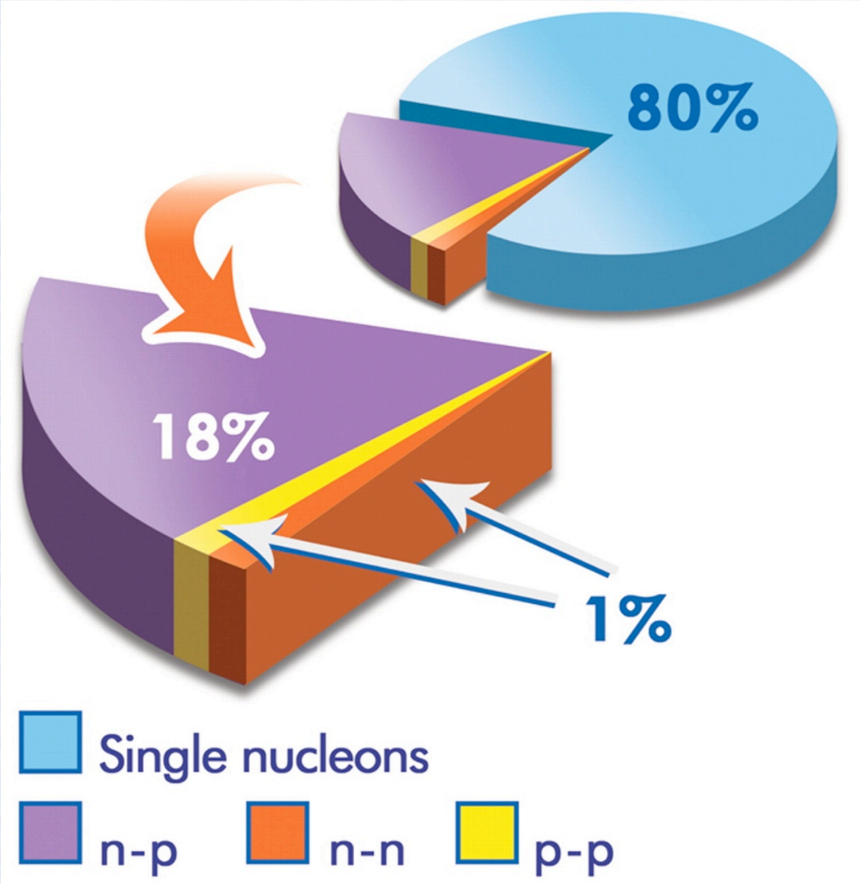
Short summary 1

- Energetic atoms ⇒ New tool to locally probe strongly-interacting atomic gases
- Systematic large-k expansions are possible

  ✓ backward scattering ⇒ contact density
- Close connection to nuclear/particle physics

JLab, Science 320, 1476 (2008)





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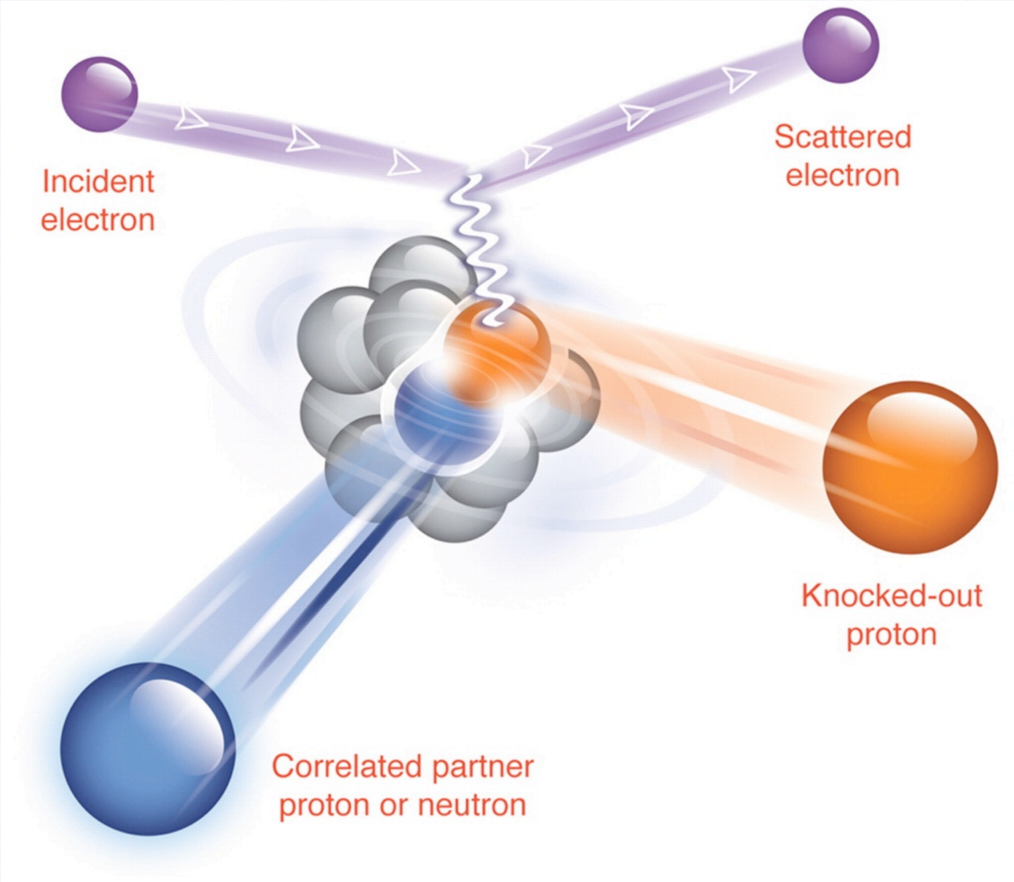


"Hard probes" are useful to reveal short-range pair correlations both in nuclei and atomic gases

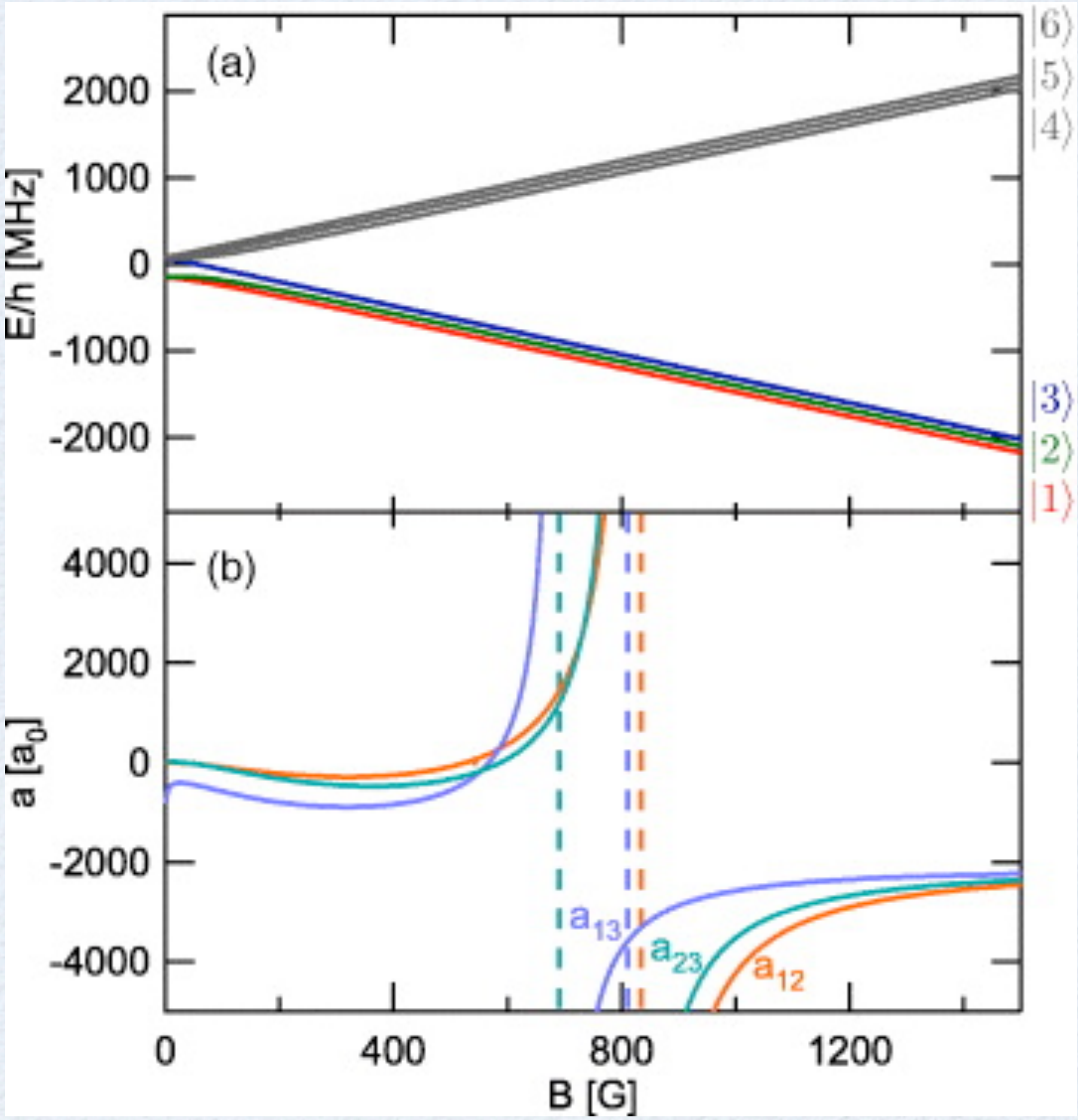
“Quark-hadron continuity” in cold atoms

3-component Fermi gas

- 3 spin states (i=1,2,3) of ^{6}Li atoms near a Feshbach resonance:

$$f(k) = \frac{-1}{ik + \frac{1}{a}}$$

- $a_{12} = a_{23} = a_{31}$



K. M. O'Hara, New J. Phys. (2011)

3-component Fermi gas

- 3 spin states (i=1,2,3) of ^{6}Li atoms near a Feshbach resonance:

$$f(k) = \frac{-1}{ik + \frac{1}{a}}$$

- $a_{12} = a_{23} = a_{31}$ ⇒ SU(3) × U(1) invariance

$$\mathcal{L} = \psi_i^\dagger \left(i\partial_t + \frac{\nabla^2}{2m} \right) \psi_i + \frac{g}{2} \psi_i^\dagger \psi_j^\dagger \psi_j \psi_i$$

- **Problem !** 3 fermions form an infinitely deep bound state (Thomas collapse)

➡ No many-body ground state :-(

3-component Fermi gas

- 3 spin states (i=1,2,3) of ^{6}Li atoms near a "narrow" Feshbach resonance:

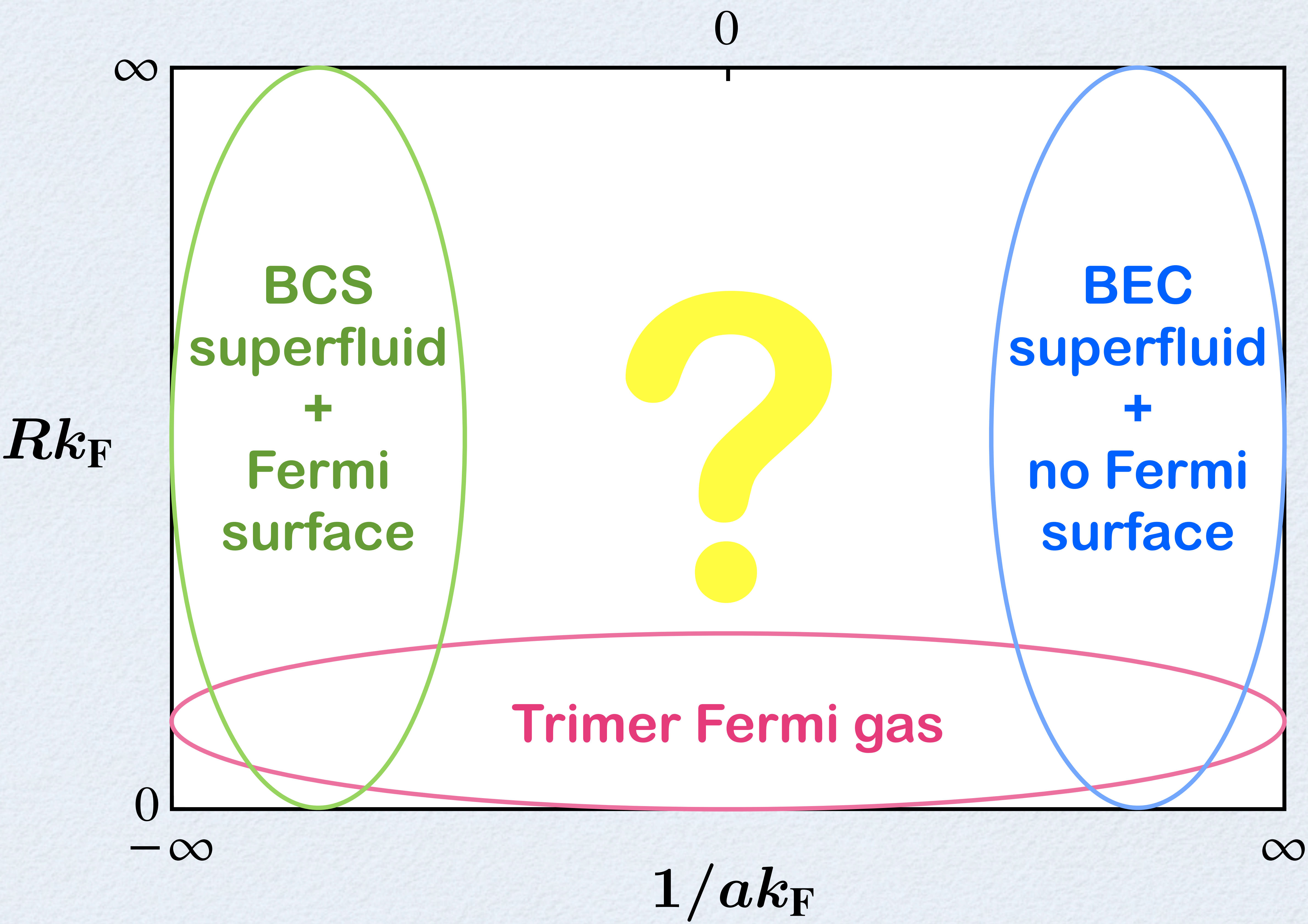
$$f(k) = \frac{-1}{ik + \frac{1}{a}} \Rightarrow f(k) = \frac{-1}{ik + \frac{1}{a} + Rk^2}$$

$r_{\text{eff}} = -2R$ is the effective range

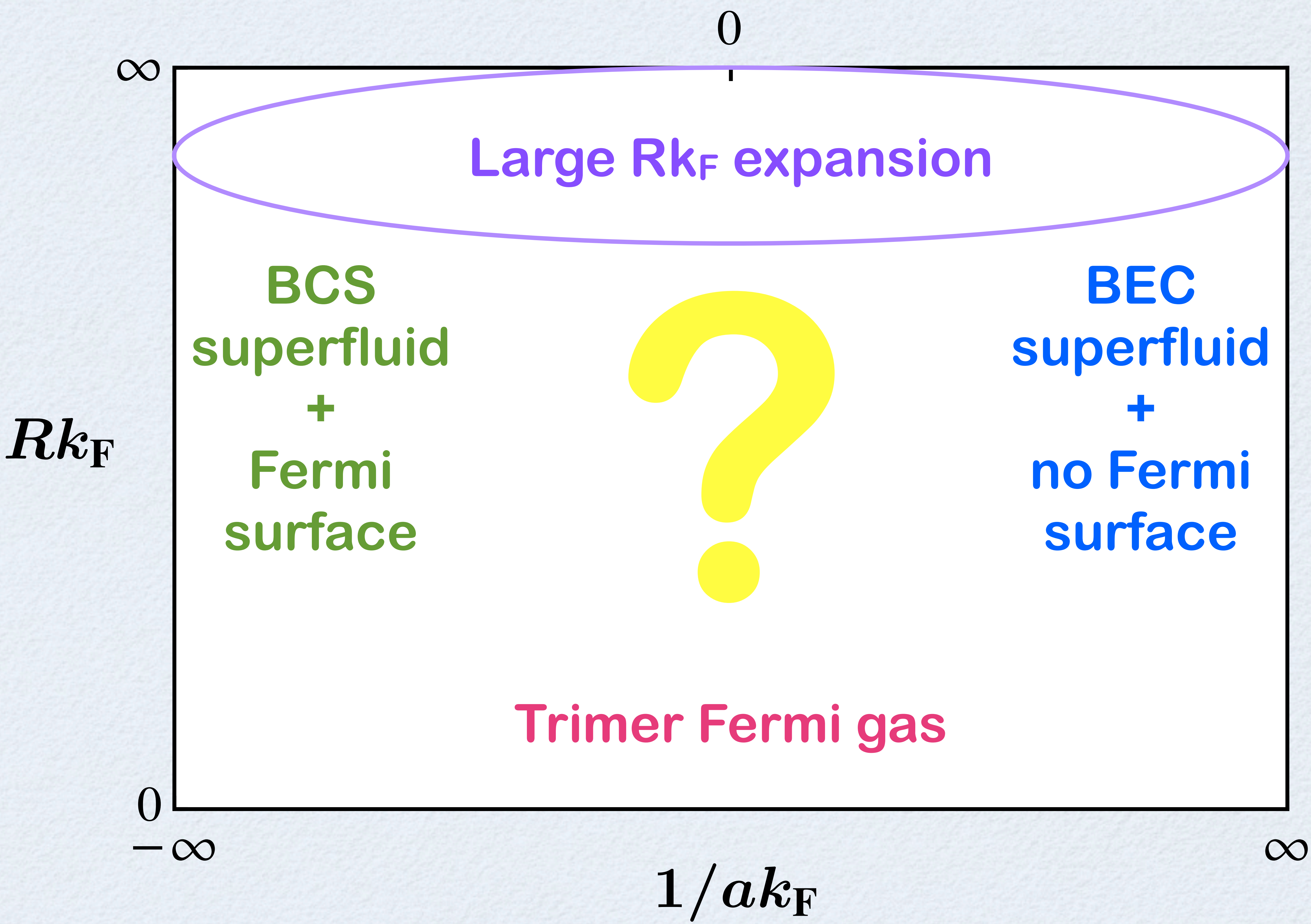
- R regularizes ultraviolet behaviors (⇒ no Thomas collapse)

⇒ Universal many-body ground state (depends only on a, R, k_F)

Phase diagram

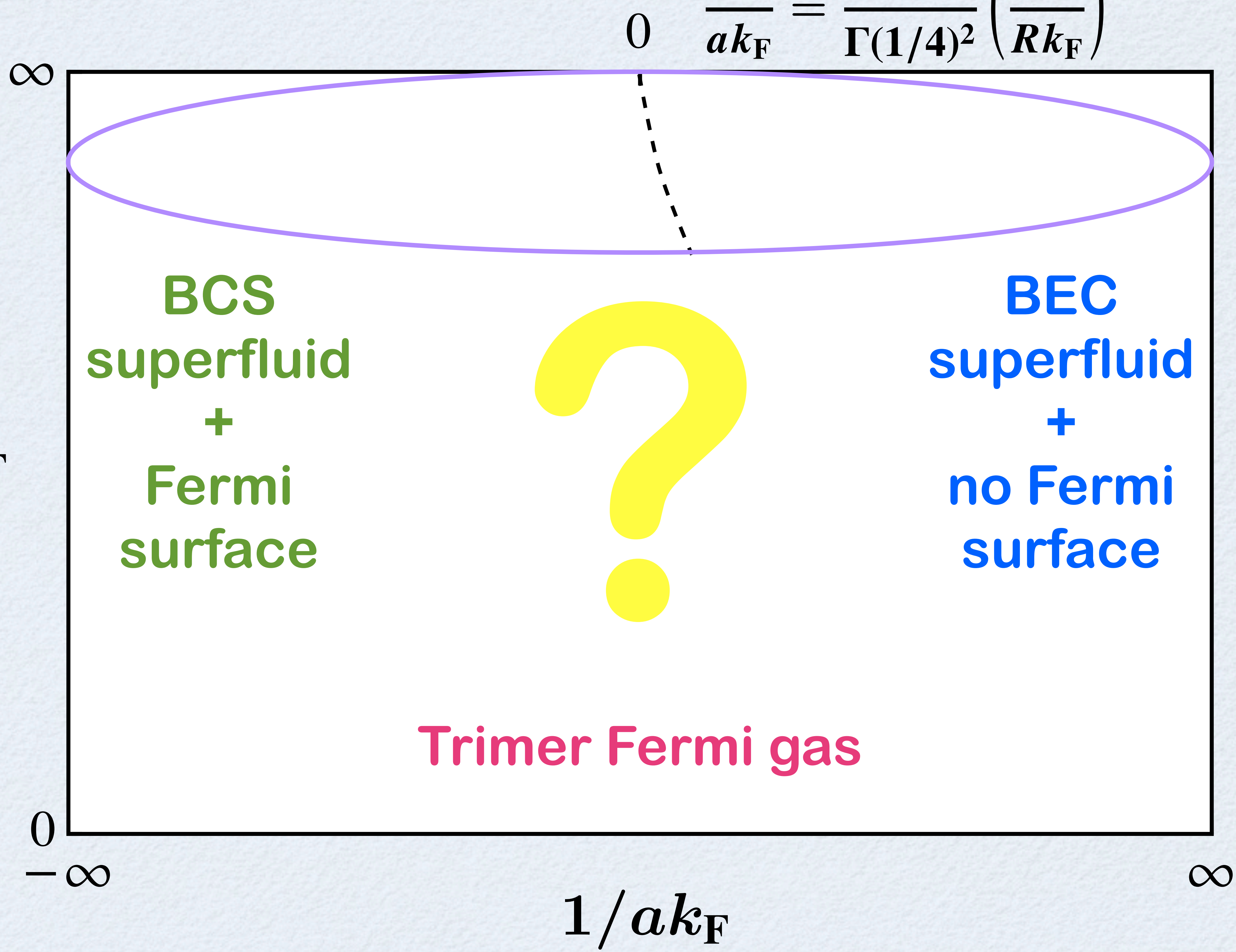


Phase diagram

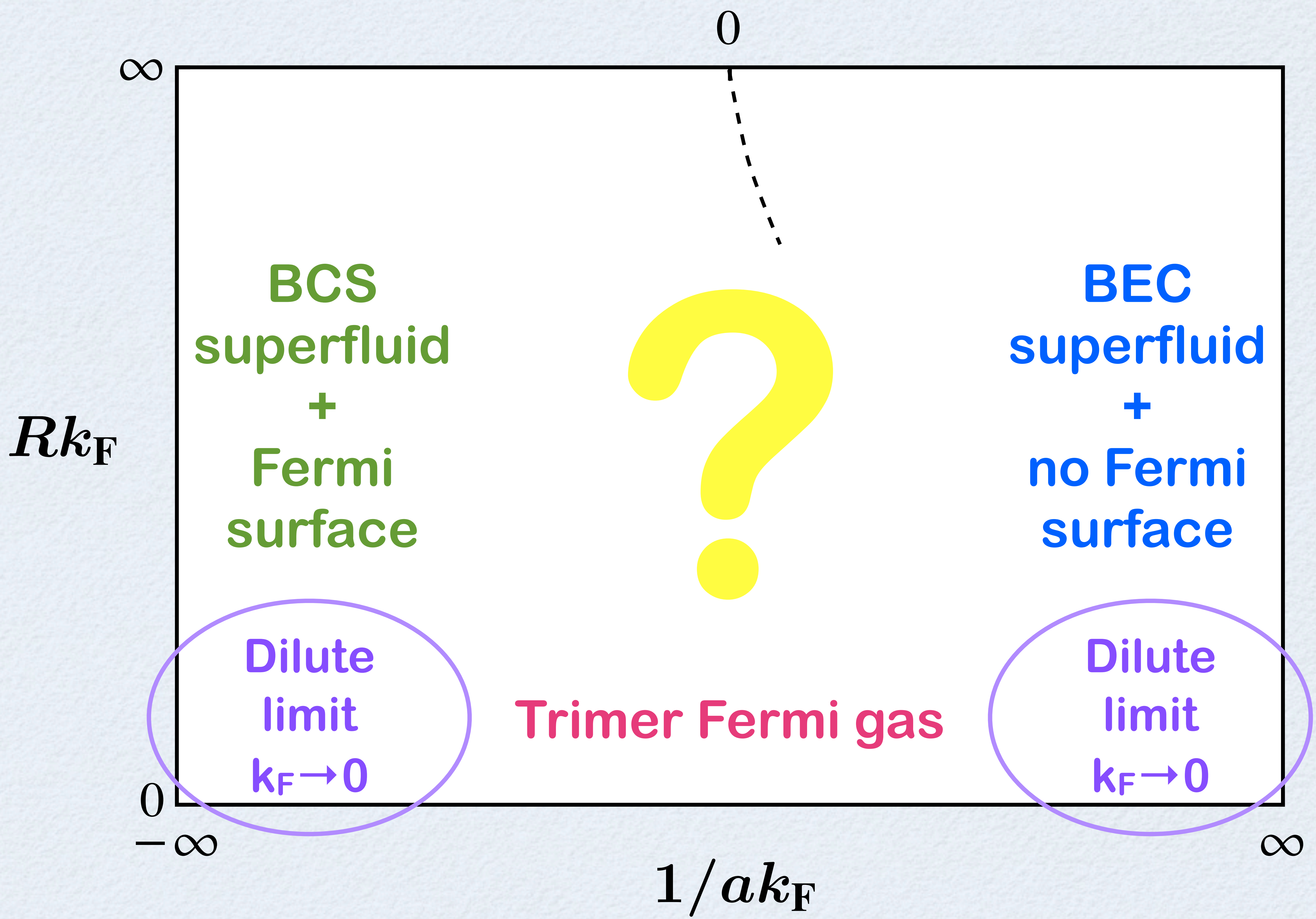


Phase diagram

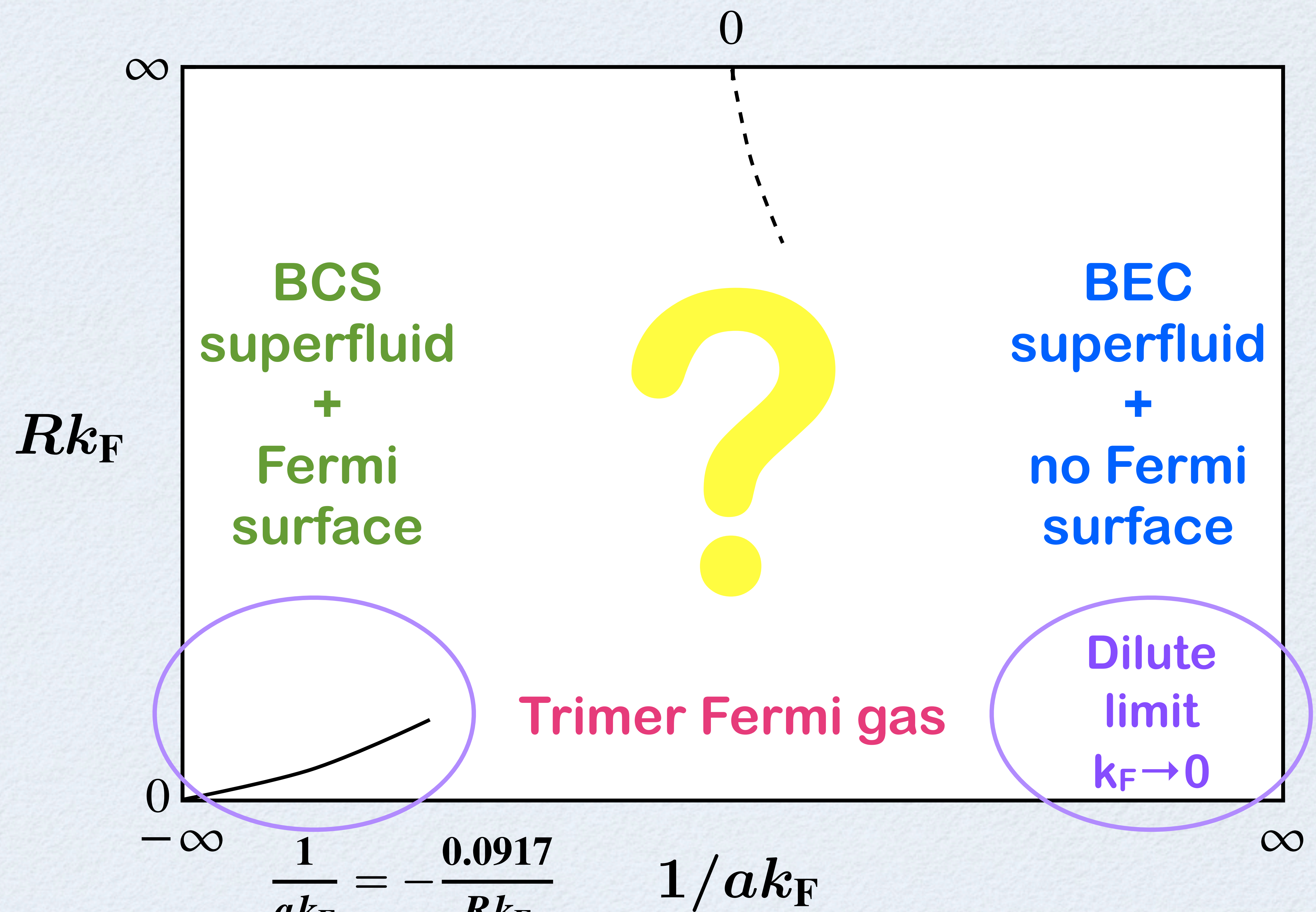
$$\frac{1}{ak_\mathrm{F}} = \frac{4}{\Gamma(1/4)^2}\left(\frac{4\pi}{Rk_\mathrm{F}}\right)^{1/4}$$



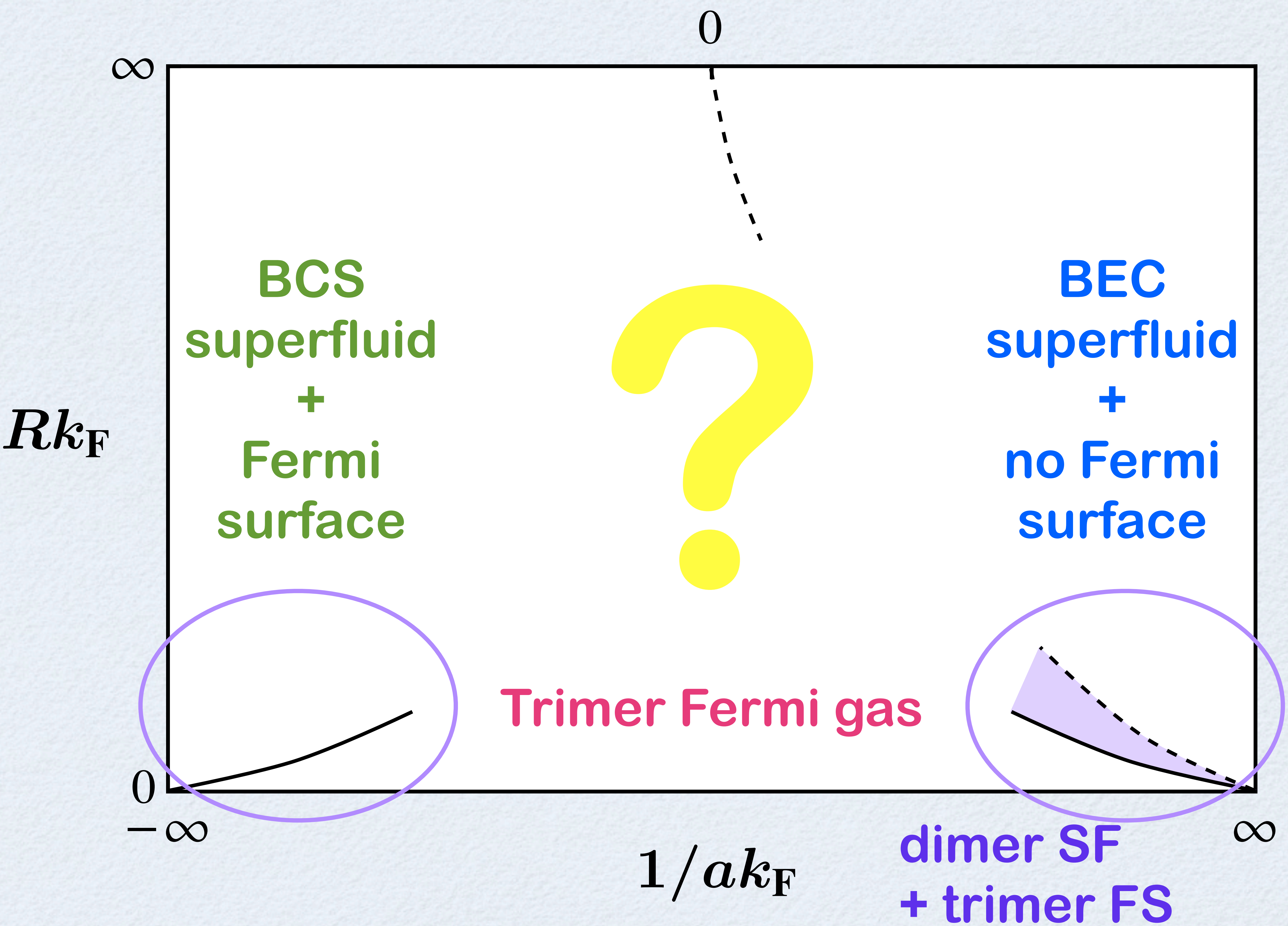
Phase diagram



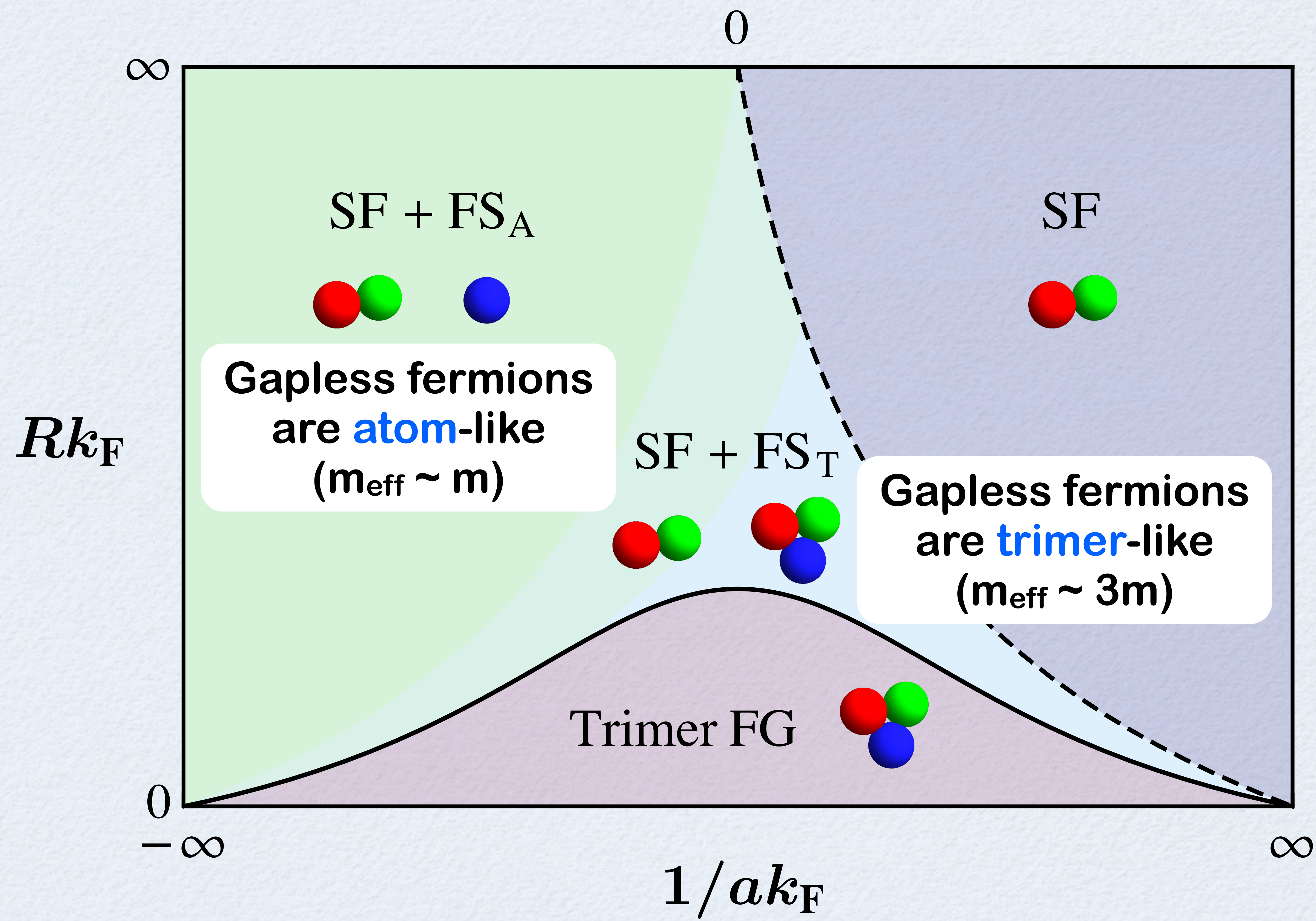
Phase diagram



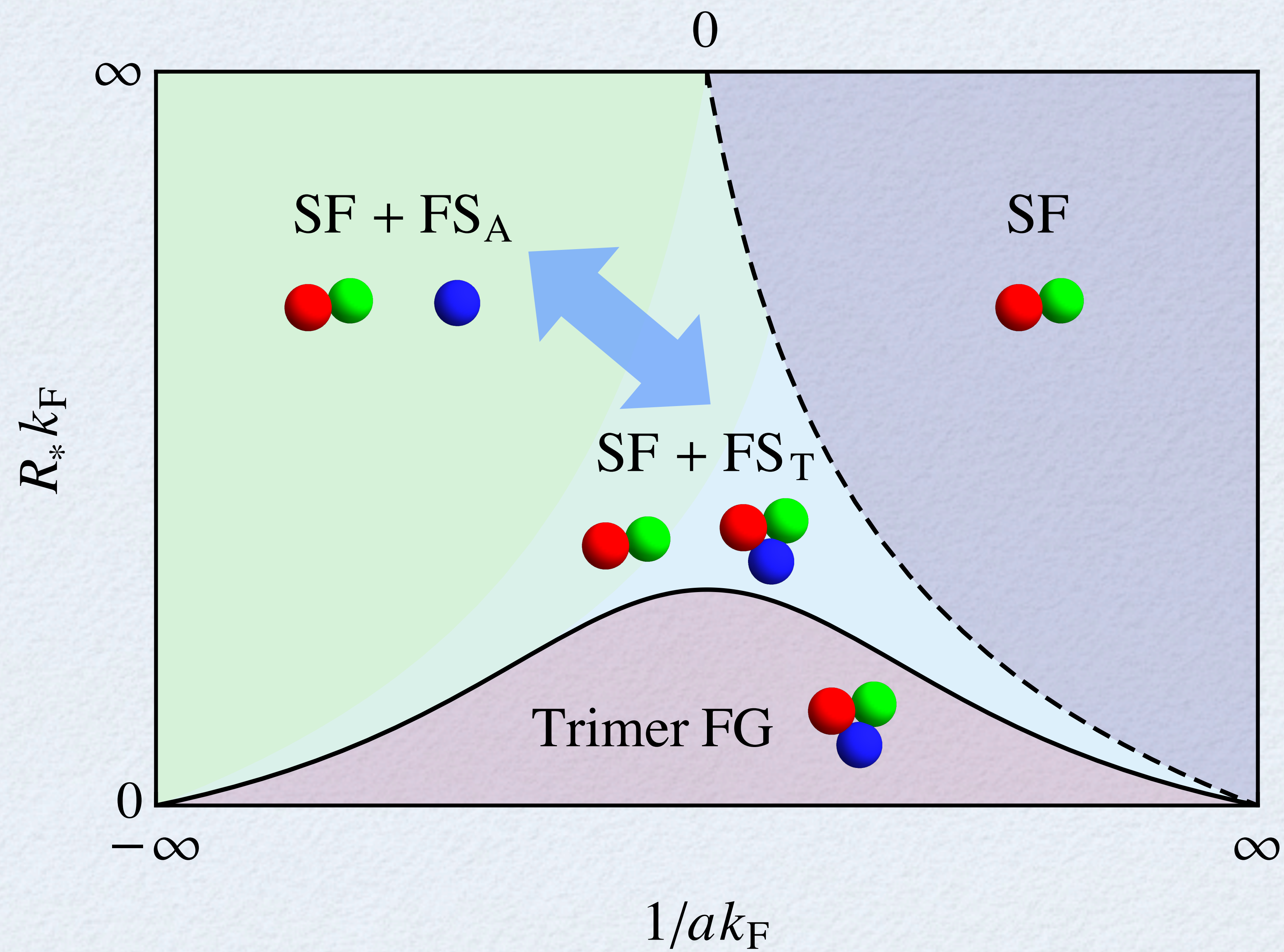
Phase diagram



Phase diagram



“Atom-trimer” continuity

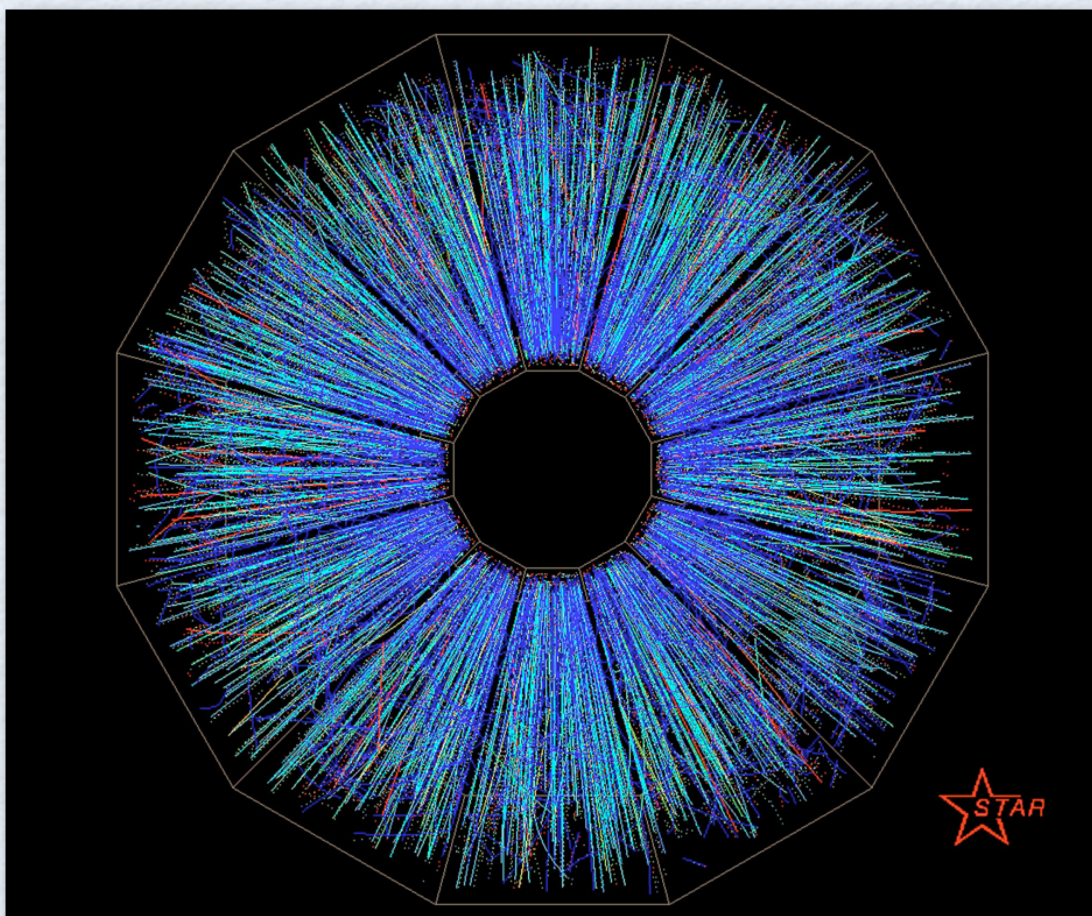


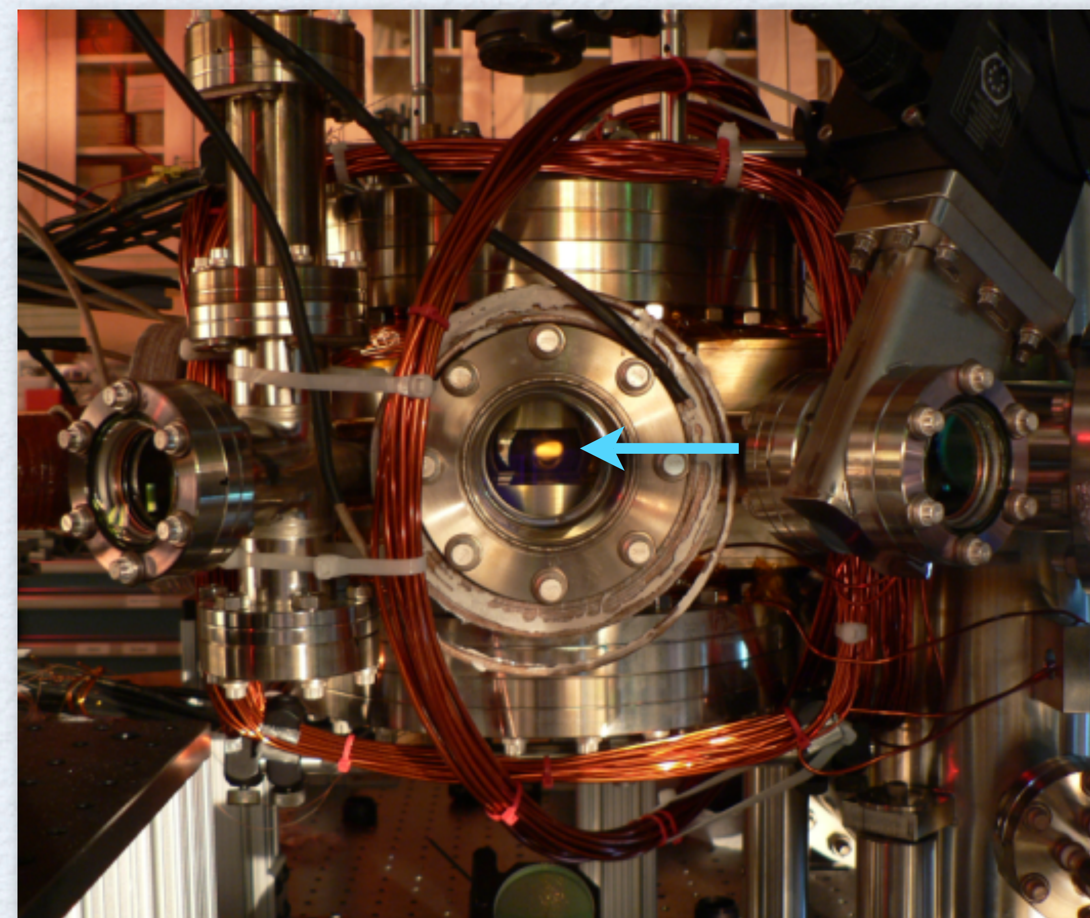
“Atom-trimer continuity” seems to survive even when identical fermions form p-wave pairs

→ **New analogy to extreme QCD ?**

Summary of this talk

Extreme QCD  **Ultracold atoms**





New ideas wanted !